Remote Sensing of Winds Using Airborne Doppler Lidar

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The wind occupies a central role in weather and climate, and its effects can be observed over a wide range of spatial and temporal scales. The wind transports heat, moisture, momentum, radiatively-active trace gases, biogeochemicals, and microscopic particles (aerosols). This redistribution and the interaction with latent heat and radiation produce weather and climate. On a daily basis these interactions can take the form of processes and features that are easily recognizable, such as convection and clouds, precipitation, jet streams, extratropical cyclones, and hurricanes.

For nearly 30 years, coherent Doppler lidar (or laser radar) has been used to remotely sense the atmospheric wind. Lidar is an acronym for light detection and ranging. The term "coherent" refers to the use of the phase information in the outgoing and incoming radiation. During lidar operation a pulse of light is emitted from the laser, scattered backward along the line of sight by clouds, dust, or other aerosols, and a Doppler frequency shift imparted by the relative motion of the scatterers. The lidar receiver converts the signals to line-of-sight (LOS) velocity as a function of range. Doppler lidar measures signals primarily from optically clear air, however velocities can be measured within or through thin clouds. Doppler lidar has a demonstrated capability to measure atmospheric dynamical processes and features over locations and scales of motion that are frequently beyond the measurement capabilities of conventional sensors. When placed on an aircraft, the measurement capability of Doppler lidar is enhanced considerably.

Scientific recognition of the relative contribution of small-scale atmospheric processes, and in particular their interaction with large-scale processes, has grown over the past 10 to 15 years. In parallel, technological advances in high-energy lasers have expanded the potential of Doppler lidar remote wind sensing for atmospheric research. The lidar remote sensing groups of MSFC, NOAA Environmental Technology Laboratory (ETL), and Jet Propulsion Laboratory (JPL) developed an airborne scanning Doppler lidar termed the multi-center airborne coherent atmospheric wind sensor (MACAWS). The centerpiece of MACAWS is a high-energy CO_2 gas laser, making this perhaps the most powerful Doppler lidar developed for airborne atmospheric research. MACAWS has the key capability to measure winds remotely over a three-dimensional volume. During operation, pulses of eye-safe laser radiation (or "beams") are directed into the atmosphere through the left side of the aircraft using a pair of internally mounted, counter-rotating germanium prisms. By refracting the lidar beam forward and aft of the aircraft heading in an alternating manner such that the LOS velocity vectors fall within a common plane, two-dimensional wind velocities may be calculated at points of intersection between the forward and aft-pointing beams (fig.154). The contribution to the Doppler shift along the line of sight due to scan angle and aircraft attitude and speed are removed by using measurements from a dedicated inertial navigation system located near the scanner. The net results are measurements of ground-relative wind velocity. The vertical distribution of wind and aerosols over a three-dimensional volume may be obtained by scanning at multiple levels with arbitrary angular separation (fig. 155).

MACAWS was flown on a short series of science demonstration flights for the first time in September 1995 aboard the NASA DC–8 research aircraft. Missions were conducted over the western United States and eastern Pacific Ocean. Highlights included the first airborne simulation of a satellite Doppler wind lidar, and the first Doppler velocity measurement within a

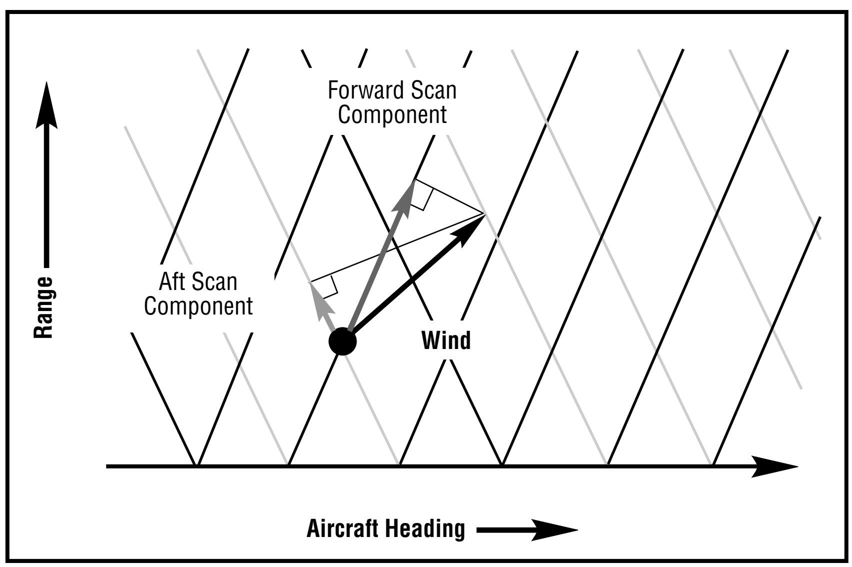

Figure 154.—Co-planar scanning method for obtaining two-dimensional wind field measurements. Scanner alternately directs lidar beam forward and aft of aircraft heading; two-dimensional wind vectors are calculated using trigonometry.

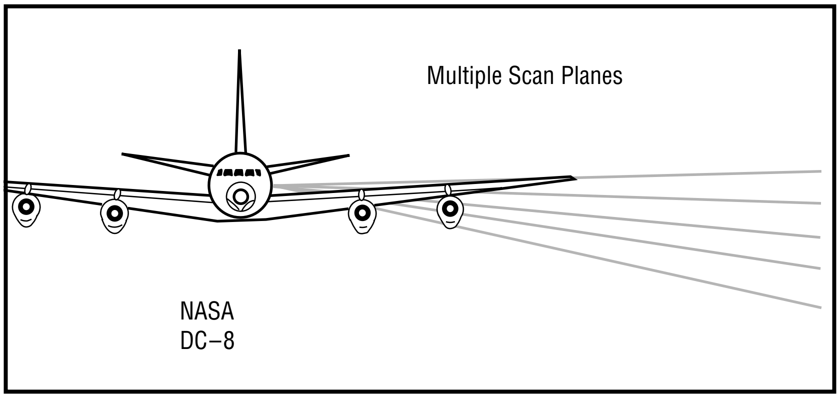

Figure 155.—Method for obtaining volumetric coverage of wind measurements by generating multiple two-dimensional scan planes. Depending on slant range, intervening atmosphere, and other factors, scan planes inclined below horizon may terminate with surface returns.

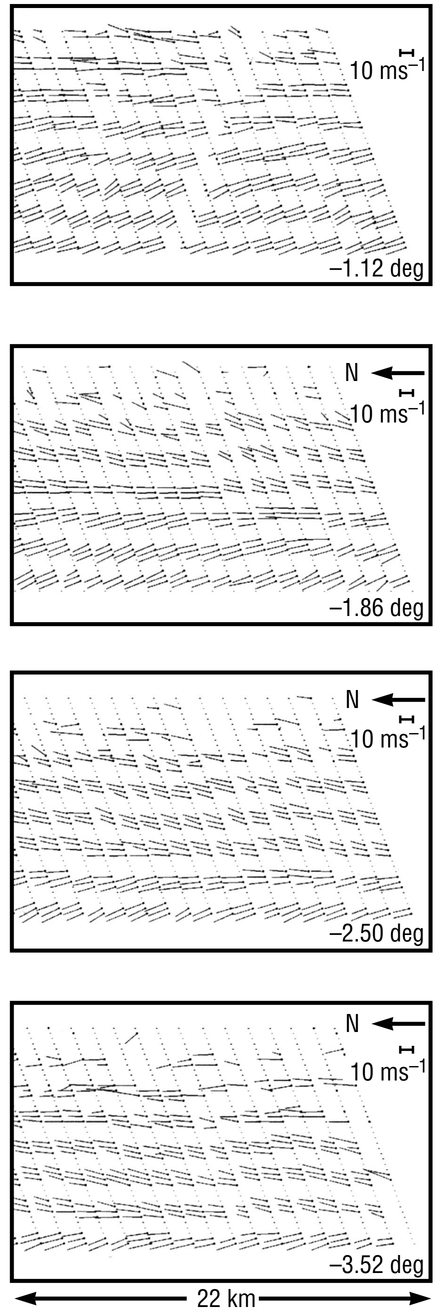

Figure 156.—Wind measurements in the marine boundary layer over the Pacific Ocean near the northern coast of Oregon; wind vectors point into the wind. Figure shows vertical distribution of winds measured within four scan planes. Aircraft altitude was ~900 m (3,000 ft) above sea surface, and approximately 100 m (330 ft) above the top of the boundary layer.

hurricane. An example of multilevel wind measurements in the Pacific marine boundary layer is shown in figure 156. Additional flights were made in June 1996 over the Pacific northwest and central United States. Highlights included the first Doppler lidar intercomparison with near-sea wind surface measurements by a space-borne scatterometer, ERS–2.

Observing system simulation experiments (OSSE's) indicate that global wind measurements from space with Doppler lidar will significantly improve the understanding of the atmosphere while simultaneously improving the capability to make better forecasts. In the absence of a heritage of satellite Doppler lidar wind measurements, performance simulations with measured—rather than simulated—data are highly desirable to reduce modeling uncertainties and to begin to develop the necessary interpretive skills. Ground-based lidar measurements alone do not address all design and performance-related issues. Measured data are invaluable for evaluating and improving OSSE's, which are used to quantify the benefit of lidar compared to existing measurement systems. The results of such simulations critically depend on instrument design, which is currently focused on instruments in the small-satellite class. Constraints on satellite power, mass, volume, and heat rejection must be carefully evaluated against performance. Through appropriate aircraft maneuvers, MACAWS can simulate the Doppler wind lidar perspective from space in order to address a variety of issues, including optimum scanning strategies, verification and improvement of Doppler signal processing algorithms, velocity retrievals at marginal signal levels, impact of spatial wind variability, effect of aerosol vertical gradients, velocity distribution in and around clouds, and Doppler velocity correction using land and ocean surface returns. Clouds will constitute a frequent scattering target for spaceborne lidar; annually over 60 percent of the globe is covered by cloud of some type at some level. MACAWS can be used to assess cloud porosity, cloud-free line-of-sight, cloud dimensions, and optical properties. All of these factors must be taken into account when assessing the representativeness of satellite Doppler lidar wind measurements, and ultimately the impact of these measurements on climate and global change studies and numerical weather prediction.

Long-term applications of MACAWS measurements will address a broad range of issues in atmospheric dynamics, climate, and hydrology, including the role of unresolved processes in hydrological and climate numerical models, improvement in mesoscale modeling and predictive capabilities, and more realistic simulations of prospective satellite Doppler wind lidar. MACAWS will be used as part of the validation effort for the NASA scatterometer (NSCAT) which measures global sea surface winds. Moreover, plans include studies of extreme weather phenomena which can affect sustainable growth.

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University/Industry Involvement:
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Biographical Sketch: Dr. Jeffry Rothermel is an atmospheric measurement specialist within the Earth System Science Division of MSFC's Space Sciences Laboratory. He leads an intergovernmental agency team which conducts airborne atmospheric research, and satellite validation and simulation using a jointly developed coherent Doppler laser radar. Rothermel also leads a team within ESSD which conducts observations and modeling of aerosol properties with the goal of better quantifying direct and indirect aerosol effects on climate and global hydrology. Rothermel earned a Ph.D. (atmospheric science) from Purdue University, and has been with MSFC for 7 years.